SECTION II.—GENERAL METEOROLOGY.

THE ORIGIN OF THE WIND.

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1. On careful consideration it appears that the wind plays a rôle of fundamental importance for the earth and all life upon it. Without the wind no cloud can be brought to land; no precipitation would fall upon the earth; no rivers would exist. The mountains, indeed, in consequence of the hot sunshine would weather down but no brooks or rivers would remove the weathered fragments. Thus without the action of the wind the earth's surface would take on an appearance entirely different from what it now has. Its absence would also threaten the existence of organic life. Plants and animals would indeed be able to exist in the seas, but this would be impossible on the absolutely arid land surfaces. Man on a dry earth is an inconceivable combination.

The energy that forms the living force of the wind, and of which we use an infinitessimal part in order to drive our ships and windmills, has of course originally come to the earth as heat from outside. This outside heat is then transformed into the energy of motion or kinetic energy, in the same way that heat is transformed into kinetic energy in a steam engine.

2. In a steam engine there is a source of heat, viz, the boiler, and a source of cold, viz, the condenser. In the atmosphere the broad ocean with its warm surface water is the source of heat, while the mountains and the ice cover of Greenland and the icy Antarctic continent are the sources of cold. The wind originates between these regions of opposite climatic characteristics.

3. In order to understand how this is brought about I have carried out the following experiment. A large glass-sided tank 50 cm. by 50 cm. by 5 cm. was filled with water. Two sets of metallic cells, similar to the heating coils of our dwellings, were then suspended in this tank. Hot water passed through one set of these cells and cold water through the other. The feed and discharge pipes were carefully insulated against heat, and the flow of warming or cooling water was maintained by the difference in level between the water supplies contained in two pairs of large wooden vats of considerable volume and capacity for heat. The temperature differences used in the cells were small but constant.

4. Like all experiments with heat, these were very tedious. First, the water in the glass experimental tank had to stand for two days, that it might assume the temperature of the room as closely as possible. Then the experiment was started and its conditions maintained for several hours until well established. Only after attaining this established condition was the next step taken, viz, the insertion of a small quantity of potassium permanganate which revealed the movements of the water under the strong illumination of an arc light. This enabled one to measure the circulation that had been established.

5. The results of the experiment were as follows: If the source of heat (the warm coil) stood at the same level as the cold source, then the water stood still; but as soon as the warm coil was lowered there began a circulation whose intensity was in proportion to the increase in the difference in level between the warm source and the cold source.

6. This result, although it is so simple, is nevertheless of the greatest importance for a correct understanding of the atmospheric processes. If the sources of warm and cold in the atmosphere are at the same level, they then induce no wind; precisely as a steam engine can perform no work when the pressure in the boiler is equal to the pressure in the condenser. The extensive [cold] ice surfaces of the North Polar Ocean can, therefore, produce no wind because they are at the same level as that of the warm ocean to the south. For the same reason the Siberian tundra, although it is cold enough, does very little to produce and maintain the wind. On the other hand, the high extensive ice-covered surface of Greenland produces far more wind than has been heretofore suspected. On this glacier is really the place where a first-order meteorological station should be established, preferably on the southeast side, which slopes toward the warm Atlantic Ocean. Here we find a gigantic heat engine which is only exceeded by the corresponding one on the border of Antarctica.

7. In the Northern Hemisphere there are, besides Greenland, many mountain chains and high plateaus whose contributions to the wind should not be underestimated. For example, the Pyrenees, the Alps, the Carpathians, and also the Scandinavian highlands, whose location as antagonistic to the Gulf Stream give rise to the European storms of winter. In Asia, the monsoon arises from the contrast between the Himalayas and the high Thibetan Plateau on the one hand and the warm Indian Ocean on the other.

8. The conditions in the Southern Hemisphere are specially grand and simple. In the coastal region of Antartica, during the Antartic winter, exist powerful and continuous winds, evidently caused by the extensive high cold surface of the continent in contrast with the surface of the warm surrounding ocean. Here is found the incomparably largest wind factory on our planet.

9. We may now return to the experimental tank, limiting ourselves to a case where the cold source stands at a higher level than the warm source. After introducing the permanganate of potash into the center of the tank, as described in 4, the color is rapidly drawn around so that a continuous band of colored water is produced, as represented in figure 1. The color then encroaches more and more upon the still uncolored region within the continuous colored band, until eventually there remains only a narrow streak which extends from W, the source of heat, to C, the source of cold. This stage is shown in figure 2. This inclined streak becomes steadily thinner and gradually passes into a surface which also eventually becomes completely colored and finally disappears.

10. The tank now shows two sharply marked level surfaces, one of which passes through the highest point of the cold source and the second passes through the lowest point of the warm source. These surfaces divide the mass of water into three strata, an uncolored superficial layer, the colored intermediate layer, and the uncolored bottom layer. From the circumstance that no color passes over from the intermediate layer into either of the two uncolored layers, whereas the latter

remain clear, we conclude that there is no interchange of water between them and the intermediate layer. The three strata of water are wholly insulated from one another.

11. We have already discovered that the intermediate layer is in more or less rapid circulation, as indicated by the arrows in figures 1 and 2. By introducing permanganate of potash into the superficial and the bottom layers we can establish the fact that the water is there standing still.

12. The distribution of temperature within the tank is now investigated by dipping into it a small thermometer on a delicate thread, placing the bulb at different depths and reading the temperatures through the glass sides of the tank. We thus find that the bottom layer has the temperature of the cold source and that the superficial layer has the temperature of the warm source, while there are two temperatures in the intermediate or colored stratum. In this stratum the water below the

and therefore form no solenoids. The inclined isosteric surfaces that lie along the inclined streak, on the other hand, intersect the isobaric surfaces thereby giving rise to a system of solenoids that is localized in the inclined streak. In this streak, therefore, lies the driving source of the whole water motion in the tank.

14. If we compare the heat engine represented by the arrangements of figure 2 with a steam engine, then W corresponds to the engine boiler, C to the condenser, and the driving mechanism of the engine is the inclined streak.

15. In order to compute the energy developed by the heat engine of figure 2 it is necessary to introduce into a system of pressure-and-volume coordinates, the various conditions experienced by a particle of water during a complete circulation of the whole mass of water. The resulting curve of condition incloses a surface equal to the energy, A, developed by a gram of water in making one complete circuit. When A is multiplied by the total mass, M, of the water in circulation the product is the
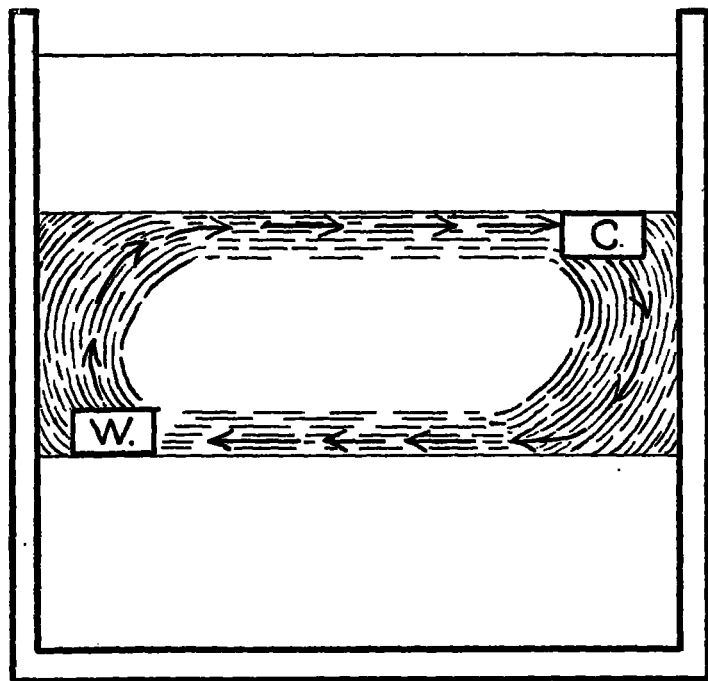

FIG. 1.—Cross section of glass-sided experimental tank showing the circulation set up by the cold cell, C, and the warm cell, W, as revealed shortly after introducing the permanganate of potash. Above C and below W are the regions of clear, unaffected, quiescent water. The region lying between C and W has not yet been stained by the permanganate.

FIG. 2.—The same cross section of the tank after a further lapse of time. The un-shaded, spindle-shaped area lying obliquely between W and C is the immediate predecessor of the inclined solenoidal streak or surface. Above C and below W remain the uncolored regions of unaffected, quiescent water.

inclined streak of figure 2 is colder than the colored water above the streak. The two horizontal level surfaces and also the inclined streak are all characterized by marking sharp changes of temperature. There are, therefore, four thermally different layers of water in the tank under these conditions; the layers are so arranged that warmer water always rests upon colder water.

13. Since the density of the water can in this case only depend upon its temperature, therefore so far as density is concerned there must also be four different layers of water in the tank, and they are so arranged that the lighter water always rests upon the heavier (the less dense upon the more dense). Where sudden changes in temperature occur there also must be sudden changes in density, i. e., the isosteric surfaces must there mutually converge. In the two level boundary surfaces the isosteric surfaces lie horizontally; that is, they are there parallel with the horizontal isobaric surfaces. These two systems of surfaces do not there mutually intersect
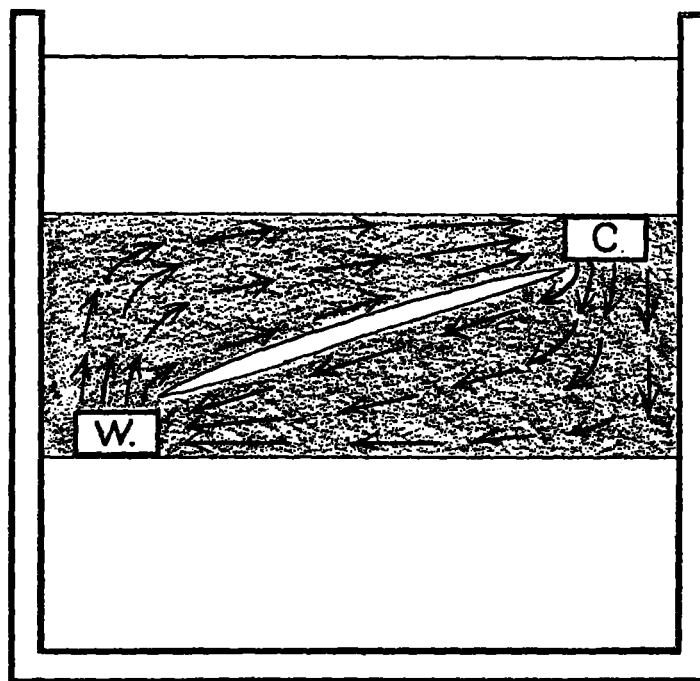
total energy developed in making one complete circuit. If T seconds are required for the whole mass, M, to make one circuit, then the quantity of energy, E, that is delivered per unit of time is

$$E = \frac{MA}{T}. \qquad (1)$$

16. But the quotient M/T is equal to the quantity of water, m, that flows through any given section of the stream in one second; hence

$$E = mA, \qquad (2)$$

and A is nothing else than the number of solenoids that are in the inclined streak. The energy delivered by the heat engine in figure 2 is, therefore, equal to the flowing mass of water expressed in grams per second multiplied by the number of Bjerknes solenoids in the inclined streak.

17. The above formulas express the energy in absolute units; a horsepower contains 736×10^7 of these units. Therefore

$$P = \frac{mA}{736 \times 10^7} \qquad (3)$$

where P is the developed energy expressed in horsepowers. In the atmosphere and the ocean problems it is more convenient to employ tons instead of grams; therefore we write

$$P = \frac{NA}{7360} \text{ HP.} \qquad (4)$$

where N is the mass of moving air or water expressed in tons per second of the C. G. S. system. A is as before the number of solenoids in the inclined solenoidal surface or streak.

18. The circulation represented in figure 2 can also be conceived at two different currents of water; the one current consisting of cold, specifically heavier water that flows down from the cold source toward the warm source; the other current of warm, lighter water that rises from the source of heat and flows toward the source of cold. There are, in fact, two actual waterfalls, the one of denser water that sinks and the other of lighter water that rises. Both these falls develop kinetic energy in the same way as do the waterfalls of our rivers. The only difference is that, instead of the total specific gravity of the water of the river computation, we here have to employ the difference in specific gravity between the flowing and the surrounding, adjacent water. This is a natural consequence of the Archimedean principle of pressure of adjacent surrounding water against the flowing water. Employing the thus reduced specific gravity, the actual height of the waterfall, and the stream discharge, the computation of the energy gives the same result as does the solenoidal formula.

19. One can also compute the correct amount of developed energy by employing the actual specific gravity and the height of the waterfall if a corresponding reduction is applied to the mass of the flowing water; or we may use the actual specific gravity and the stream discharge in combination with an appropriately reduced height of waterfall. I have found the last of these procedures the most practical because that method permits the direct substitution of tons of flowing water or air for the cubic meters of water of the river they are compared with.

20. In the atmosphere, the snow and ice covered mountain tops and high plateaus correspond with the cold source C' of figure 2, and the warm surface water of the warm ocean with its warm currents correspond with the warm source W. The circulation of the air that exists in the atmosphere is of the same kind and nature as the circulation of the water shown in figure 2. Thus the air warmed above the warm surface of the ocean rises and spreads out horizontally until it comes in contact with the cold mountain tops. Here it cools, sinks, and returns along the earth's surface to the warm ocean only to repeat the circulatory process. The warm current of air above and the cold current below are separated by an inclined surface corresponding to the inclined streak of figure 2. This atmospheric surface contains the solenoids that induce and maintain the atmospheric circulation. The amount of kinetic energy developed by the two air currents can be estimated according to the manner above described, either employing formula (4) or by comparing the currents with the waterfalls.

21. The circulation of the water in the atmosphere is also like the scheme of figure 2. In this case the source of heat is the warm ocean surface whose water particles

evaporate and rise in a gaseous form into the atmosphere; the cold source, C, is the point in the atmosphere where the water vapor is cooled and condensed into rain or snow. These forms fall and form rivers that flow back to the ocean, i. e., back to the source of heat W. In this circulation an immense amount of kinetic energy is produced—of it we use a very small fraction in our hydroelectric and water-power plants. The largest part of the energy of this circulation is consumed in producing the wind, as the Swedish oceanographer, Prof. Otto Peterson, has shown. The computation of this energy by the above methods offers no special difficulties.

22. The ocean currents also appear to follow the scheme of figure 2. Let us consider, for instance, the Gulf Stream. It has its origin in the great sargasso vortex which carries the sun-warmed ocean water of the Tropics downward to a depth of 600 meters. This is the source of heat W, of the Gulf Stream. From here the warm Gulf Stream water flows along the Atlantic trough northward until it reaches the ice of the Arctic Ocean. This ice corresponds to the cold source C' of figure 2; it cools the Gulf Stream water which sinks to the depths along which it flows back as a cold undercurrent toward W in the Tropics. Here it is again warmed, rises to the surface, and again wanders northward. On its northward course the upper portion of the Gulf Stream becomes shallower; under the Tropics it is 600 meters deep but at Spitzbergen it is only 200 meters deep. The surface dividing the warm upper stream from the cold undercurrent is therefore inclined like the sloping streak of figure 2; therefore, this streak contains a number of solenoids, amounting to about 150,000, according to hydrographic observations. The mass of water that flows in the Gulf Stream is estimated at 25,000,000 cu. m. per second. Therefore, and by equation (4), the Gulf Stream delivers about 500,000,000 HP. This amount of energy is, of course, applied to the task of driving the Gulf Stream itself, whereby the internal friction of the water reconverts it into heat. The Gulf Stream may be compared to a river that discharges 25,000,000 cu. m. per second over a waterfall $1\frac{1}{2}$ meters high. Such a waterfall would develop the same amount of energy as does the Gulf Stream.

23. In order to be able to make such numerical estimates of the energy of the atmospheric currents we must have the proper data at appropriately located mountain stations and kite stations.

24. For the present we see from the foregoing that the simple experiment presented in figure 2 possesses many large and important counterparts in the atmosphere and the hydrosphere. Indeed, it can hardly be otherwise since it is itself a picture in miniature of the powerful heat engine that creates the currents of the wind and the ocean.

SOME RECENT RESEARCHES ON THE MOTION OF FLUIDS.

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1. The early attempts of mathematicians to calculate the distribution of velocity in a fluid containing a solid body either at rest or in motion, led to conclusions which do not agree with experimental results.

In the continuous potential flow of a perfect fluid it was found, for instance, that a fluid of infinite extent offers no resistance to uniform motion of the body, pro-